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THE SEARCH FOR METEORITES WITH COMPLEX EXPOSURE HISTORIES AMONG ORDINARY CHONDRITES WITH LOW ^{3}HE/^{21}NE RATIOS.

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Introduction: In calculating cosmic-ray exposure ages of meteorites it is generally assumed that the meteoroids were expelled from a shielded position within their parent body and then experienced a single stage exposure before colliding with Earth. The combination of noble gas and radionuclide measurements in several large meteorites, such as Jilin and Bur Ghelaui, have revealed complex exposure histories: i.e. an initial exposure on the surface of an asteroid (or within a meter-sized meteoroid), followed by a second exposure as a smaller object. In fact, orbital dynamics calculations predicted that at least 30% of the meteorites arriving on Earth experienced two- or multiple-stage exposure histories [1]. More recently, after the recognition that the Yarkovsky effect plays an important role in delivering meteorites from the asteroid belt to Earth-crossing orbits, it was confirmed that complex exposure histories should be common [2]. Nevertheless, despite the ability to measure a wide range of radionuclides with accelerator mass spectrometry (AMS), only a few meteorites with complex exposure histories have been identified [e.g. 3,4]. The question is whether the relatively paucity of complex exposure histories is real or have we simply overlooked complex-exposure histories. In this work we focus on meteorites with low ^{3}He/^{21}Ne ratios, since it is known that most meteorites with complex exposure histories have relatively low ^{3}He/^{21}Ne ratios, i.e. the ^{3}He/^{21}Ne ratio is below the 'Bern-line'. Several hypotheses have been suggested for these low ^{3}He/^{21}Ne ratios, including solar heating in low-perihelion orbits, shock-related diffusion of He during the collision that ejected the meteoroid, or an artifact of high shielding condtions [4]. The first two hypotheses seem to be supported by low radiogenic ^{4}He concentrations in samples with low ^{3}He, whereas Monte Carlo calculations have shown that some of the low ^{3}He/^{21}Ne ratios may be due to high shielding conditions in objects with radii > 1m [5].

To elucidate these issues, we selected 15 samples with known noble gas concentrations [6] for radionuclide studies and obtained aliquots of the samples adjacent to those measured for noble gases. The specific goal is the identification of complex exposure histories among samples having low ^{3}He/^{21}Ne ratios. All samples have ^{3}He deficiencies of >20% relative to the 'Bern-line' (Table 1). Most of the selected samples also have low ^{22}Ne/^{21}Ne ratios (≤1.1), indicative of high shielding during most of their cosmic-ray exposure (Table 1), whereas one sample (Suizhou) was selected because of its relatively low ^{81}Kr concentration [7]. In addition, we selected QUE 93021, for which initial radionuclide results suggested a short exposure age. Here we present cosmogenic ^{10}Be, ^{26}Al and ^{36}Cl in stone and metal fractions for the 16 ordinary chondrites listed in Table 1.

Experimental procedures: Samples of 0.5-1.5 g were gently crushed in an agate mortar and metal was separated with a magnet. The metal was cleaned in a ultrasonic bath with 0.2N HCl and concentrated HF to remove attached troilite and silicates, respectively. Procedures for sample dissolution and chemical separations of ^{10}Be, ^{26}Al and ^{36}Cl were described previously [8]. All radionuclide concentrations were measured by AMS at the Lawrence Livermore National Laboratory.

Results and Discussion: Results are listed in Table 1. We use two criteria to determine whether or not the radionuclide and noble gas concentrations are consistent with a simple exposure history:

1) Samples with ^{10}Be concentrations below 20 dpm/kg in the stone fraction are candidates for complex exposure, unless they have a short ^{21}Ne exposure age or show signs of high or low shielding conditions. Low ^{10}Be values in Enshi, Erofeevka, Pantar and Seres are due to short exposure ages, whereas low ^{10}Be values in Kaffir(b) and Long Island coincide with high ^{10}Be(sto)/^{10}Be(met) ratios indicating high shielding. The low ^{10}Be value in Nantong on the other hand is due to low shielding conditions. This leaves QUE 93021 as the only obvious case of a complex exposure history, since its low ^{10}Be cannot be explained by any of the above. From the radionuclide concentrations in the metal phase of QUE 93021 we estimate a second-stage exposure <2.5 Myr.

2) We calculated ^{10}Be/^{21}Ne exposure ages according to Graf [9]. Some of these ages are up to 80% higher than the ^{21}Ne exposure ages calculated using the formalism of Eugster [7]. This is mainly due to the selection of samples with ^{22}Ne/^{21}Ne ratios <1.1, indicative of high shielding conditions, for which the Eugster formalism is known to underestimate exposure ages. Figure 1 shows that for samples with average shielding conditions (1.1<^{22}Ne/^{21}Ne<1.2), the two ages generally agree within 20%, whereas the difference increases towards lower ^{22}Ne/^{21}Ne ratios. However, two samples clearly stand out from this general trend: the ^{10}Be/^{21}Ne ages of QUE 93021 and Seres indicate

higher shielding conditions than their $^{22}Ne/^{21}Ne$ ratios do. This suggests a complex exposure history with high shielding in the first stage and a second stage short enough (<3 My) so that the ^{10}Be still reflects the higher shielding conditions of the first stage, whereas the $^{22}Ne/^{21}Ne$ ratio is intermediate between the first and second stage. The complex exposure history of QUE 93021 was already obvious from its low ^{10}Be concentrations, but for Seres the situation is less clear-cut. The ^{21}Ne exposure age of ~0.7 Myr corresponds to reasonable ^{10}Be and ^{26}Al saturation values of 23 and 72 dpm/kg in the stone fraction, but is not consistent with the ^{10}Be and ^{36}Cl concentrations in the metal. A higher exposure age of ~1.0 My is consistent with ^{10}Be and ^{36}Cl, but not with ^{26}Al in the metal. In a complex exposure history scenario, we estimate a second-stage exposure time <0.5 Myr from the concentration of ^{36}Cl in the metal phase.

Conclusions: For a total of 15 ordinary chondrites with low $^{3}He/^{21}Ne$ ratios, we only found one or two cases of complex exposure histories, whereas all other samples are consistent with simple exposure histories. So, even for samples that were selected because they are believed to give a higher probability to find complex exposure histories, we find only ~10% of the samples to have two-stage exposure histories. Future measurements of ^{41}Ca in stone and metal fractions may aid in constraining the exposure histories of Seres and QUE 93021.

References: [1] Wetherill G. W. (1980) *Meteoritics* 15, 386-387 [2] Vokrouhlicky D. and Farinella P. (2000) *Nature* 407, 606-608. [3] Vogt S. K et al. (1993) *Meteoritics* 28, 71-85. [4] Herzog G. F. et al. (1997) *MAPS* 32, 413-422 [5] Masarik J. et al. (2001) *MAPS* 36 (submitted). [6] Schultz and Kruse H. (1989) *Meteoritics* 24, 155-172; and 2000 update. [7] Eugster O. et al. (1993) *GCA* 57, 1115-1142. [8] Welten K. C. et al. (1999) Antarct. Met. Res. 12, 94-107. [9] Graf Th. et al. (1990) *GCA* 54, 2521-2534.

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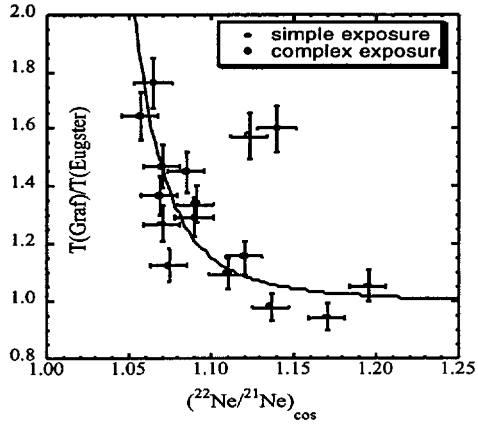

Fig. 1. The comparison of $^{10}Be/^{21}Ne$ ages according to Graf [9] with simple ^{21}Ne exposure ages according to Eugster [7] clearly shows complex exposure histories for Seres and QUE 93021.

Table 1. Nobe gas data and cosmogenic radionuclide results in ordinary chondrites with low $^{3}He/^{21}Ne$ ratios.

Sample	Class	$^{3}He/^{21}Ne$	$^{22}Ne/^{21}Ne$	^{21}Ne	^{10}Be [dpm/kg] stone	^{10}Be [dpm/kg] metal	^{26}Al [dpm/kg] stone	^{26}Al [dpm/kg] metal	^{36}Cl metal	T(exp) ^{21}Ne	T(exp) $^{21}Ne/^{10}Be$
Ambapur Nagla	H5	1.8	1.09	3.89	20.9±0.4	5.04±0.10	58.4±1.4	3.84±0.10	22.6±0.3	11.5	15.4
Changxing*	H5	3.0	1.14	1.41	21.0±0.2	4.82±0.07	71.6±1.5	3.71±0.23	22.6±0.4	5.1	5.0
Densmore(1950)*	H6	2.3	1.07	3.18	20.7±0.4	3.62±0.10	65.4±1.6	2.3±0.3	15.6±0.4	8.5	10.8
Enshi	H5	4.1	1.17	0.88	17.5±0.2	4.25±0.06	74.3±1.9	3.98±0.11	22.8±0.5	3.6	3.4
Erofeevka*	H4	1.3	1.07	1.20	17.3±0.2	-	59.4±1.6	-	-	3.2	4.7
Kaffir (b)*	H4	1.0	1.07	1.94	16.0±0.3	2.29±0.05	55.1±1.3	1.65±0.06	13.1±0.2	5.0	8.8
Kaptal-Aryk	L6	2.7	1.12	19.1	20.4±0.2	-	56.6±1.4	-	-	60.8	70.3
Laochenzhen	H5	2.4	1.07	14.2	25.4±0.5	4.59±0.09	77.4±1.6	3.57±0.11	23.2±0.3	38.4	43.3
Long Island*	L6	2.4	1.06	8.33	19.3±0.4	3.34±0.07	63.8±1.8	3.02±0.16	19.7±0.5	19.1	31.4
Nantong	H6	2.7	1.20	6.15	17.9±0.2	5.88±0.07	50.9±1.1	4.25±0.14	23.3±0.3	27.5	29.0
Nikolaevka	H4	1.5	1.11	5.71	20.4±0.4	-	54.8±1.6	-	-	18.3	20.1
Pantar	H5	3.4	1.09	1.14	19.0±0.2	2.99±0.05	77.2±1.2	2.46±0.11	18.8±0.4	3.4	4.4
Seres	H4	1.0	1.12	0.21	6.4±0.1	1.11±0.03	35.9±0.7	1.65±0.05	14.2±0.2	0.7	1.1
Slavetic	H4	3.1	1.07	2.33	22.4±0.5	3.57±0.07	77.6±1.9	2.99±0.10	20.2±0.6	6.2	8.5
Suizhou	L6	4.8	1.09	10.3	23.9±0.3	5.47±0.08	70.8±1.5	3.78±0.14	23.0±0.6	27.2	39.5
QUE93021	L5	2.0	1.14	2.49	14.3±0.3	3.36±0.04	44.0±1.1	2.91±0.10	17.5±0.3	8.5	13.6

*Finds, all other samples are falls. Noble gas data in non-Antarctic samples are from [6], those in QUE 93021 from this work. Cosmogenic ^{21}Ne concentrations are given in 10^{-8} cm^{3} STP/g, ^{36}Cl concentrations in dpm/g, and ^{21}Ne and $^{21}Ne/^{10}Be$ expsoure ages in Myr.

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